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THE d(e, e′p)n REACTION AND THE NEUTRON ELECTRIC FORM FACTOR

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The cross section for the d(e, e′p)n reaction is calculated for quasi-free kinematics in the impulse approximation including the final state interaction and the pair current contributions. Its dependence on the recoil momentum agrees quite well with recent Saclay data up to $p = 350$ MeV/c. We also show how a measurement of the cross section for quasi-elastic scattering in which one detects low energy protons may provide information on G_E^n.

The electromagnetic properties of the deuteron are of interest for several reasons: (i) the deuteron plays a central role in establishing the properties of the nucleon–nucleon interaction so that detailed tests of the two-body wave function are essential; (ii) the deuteron is the most obvious choice for a source of neutrons to obtain information on neutron form factors.

The (e, e′p) reaction recently investigated at Saclay with good energy and momentum resolution provides a powerful tool to study the electromagnetic properties of the deuteron. For quasi-free kinematics the cross section is, in good approximation, described by the plane wave impulse approximation, where it is directly proportional to the deuteron momentum distribution. The primary motivation for the Saclay experiment was in fact to probe the effects of the deuteron D-state, which should show up more clearly at higher recoil momenta.

In this letter we report on a calculation on the d(e, e′p)n reaction at quasi-free proton kinematics. For a quantitative comparison with the data the effects of final state interactions and/or the so-called pair current are included. In addition we examine the question whether the same reaction at quasi-free *neutron* kinematics can be used to obtain information about the neutron electric form factor.

The nuclear current matrix element J_μ for the $A = 2$ system can be expressed as [1]

$$J_\mu(q) = \int \mathrm{d}_3 r \int \frac{\mathrm{d}_3\tau}{(2\pi)^3} \mathrm{e}^{\mathrm{i}\tau\cdot r} \times \phi_\mathrm{f}^*(r) \hat{J}_\mu(\tfrac{1}{2}\boldsymbol{q} + \boldsymbol{\tau}, \tfrac{1}{2}\boldsymbol{q} - \boldsymbol{\tau})\phi_\mathrm{i}(r)\,, \tag{1}$$

where $\boldsymbol{q}$ is the three-momentum transfer and $\phi_{\mathrm{i,f}}$ are the initial and final nuclear wavefunctions. For quasi-free kinematics the dominant contribution is given by the PWIA (fig. 1a)

$$\hat{J}_\mu(\boldsymbol{k}, \boldsymbol{l}) = (2\pi)^3(\delta_3(\boldsymbol{l})\hat{J}_\mu^{(\mathrm{p})}(\boldsymbol{q}) + \delta_3(\boldsymbol{k})\hat{J}_\mu^{(\mathrm{n})}(\boldsymbol{q}))\,, \tag{2}$$

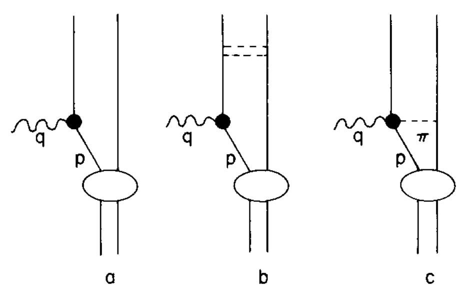

Fig. 1. Diagrams considered here: (a) PWIA, (b) final state interactions, (c) meson pair current.

where $\hat{J}_\mu^{(p)}(\hat{J}_\mu^{(n)})$ is the proton (neutron) current operator.

The final (pn) state wavefunction is given by

$$\phi_f(r) = e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \sum_S \chi_{M_S}^S \sum_T \eta_0^T ,$$

where χ and η are the spin and isospin function, respectively, and $\boldsymbol{k}$ is the relative (pn) momentum. After summing over the final nucleon spins and averaging over the deuteron spin, and making the usual non-relativistic expansion of the covariant single-nucleon current (neglecting the electron mass and keeping only the proton current in eq. (2)) the cross section in the laboratory frame can be expressed as

$$\mathrm{d}\sigma^{\mathrm{PWIA}} = \frac{\alpha^2}{E_i E_f} \frac{1}{4\pi^3} \frac{M^2}{E_{pf} E_{nf}}$$

$$\times\, \delta(E_i - E_f - E_{pf} - E_{nf} + 2M + B_d)(Z_0^2(n_f) + Z_2^2(n_f))$$

$$\times \Big[(2E_iE_f - \tfrac{1}{2}t)4\pi(G_E^p)^2 + \tfrac{1}{2}t\,\frac{\pi}{M^2}\,(F_1^p p_t)^2$$

$$- \frac{4\pi}{M} G_E^p F_1^p (E_i \boldsymbol{k}_i\cdot\boldsymbol{p}_t + E_f \boldsymbol{k}_i\cdot\boldsymbol{p}_t) \tag{3}$$

$$+ \frac{2\pi}{M^2}(F_1^p)^2\, \boldsymbol{k}_i\cdot\boldsymbol{p}_t \boldsymbol{k}_f\cdot\boldsymbol{p}_t + \frac{2\pi}{M^2}\left(E_iE_f\cos^2\frac{\theta}{2} + \tfrac{1}{2}q^2\right)$$

$$\times\, (G_M^p t)^2\Big]\, \mathrm{d}_3 k_f \mathrm{d}_3 p_f .$$

Here θ is the electron scattering angle, $\boldsymbol{p}_{i,f}(E_{pf})$, $\boldsymbol{n}_{i,f}$ (E_{nf}) and $\boldsymbol{k}_{i,f}(E_{i,f})$ are the initial and final momenta (energies) of the proton, neutron and electron respectively; $\boldsymbol{p}_t = \boldsymbol{p}_i + \boldsymbol{p}_f$, $\boldsymbol{q} = \boldsymbol{k}_i - \boldsymbol{k}_f$; t is the four-momentum transfer. The structure functions Z_0 and Z_2 are defined as

$$Z_l(p) = \int_0^\infty \mathrm{d}r\, r j_l(pr) u_l(r) ,$$

where $u_0(r) \equiv u(r)$ and $u_2(r) \equiv w(r)$.

Corrections to the PWIA are calculated as follows. The effect of final state interactions (fig. 1b) is included for the $l = 0$ states

$$\phi_f = \phi_f^{\mathrm{PW}} - \left(j_0(kr) - \frac{v^{000}(r)}{r}\right)\chi_0^0 \eta_0^1$$
$$- \left(j_0(kr) - \frac{v^{011}}{r}\right)\chi_{n_f}^1 \eta_0^0 . \tag{4}$$

Of the various exchange current contributions only the pair current (fig. 1c) which appears to be the dominant contribution [2] has been included. The nucleon form factors are taken from ref. [3]. The deuteron wavefunction and the scattering wavefunction v^{000} have been calculated from the Reid soft core (RSC) potential [4]; v^{011} is obtained from the potential III of Malfliet and Tjon [5]. (The latter potential yields the same phase shift for $l = 0$ as the coupled $^3S_1-^3D_1$ RSC potential.)

Quasi-free proton kinematics. In fig. 2 the calculated cross section as a function of the recoil momentum p is shown for various cases: (A) pure S-state deuteron ($Z_2 = 0$), calculated in PWIA, (C) full deuteron wavefunction in PWIA, (B) full deuteron wavefunction plus final state interactions, (D) full deuteron wavefunction including exchange currents. It is seen that the effects of final state interactions and exchange currents are opposite and largely cancel. Moreover even at larger p the

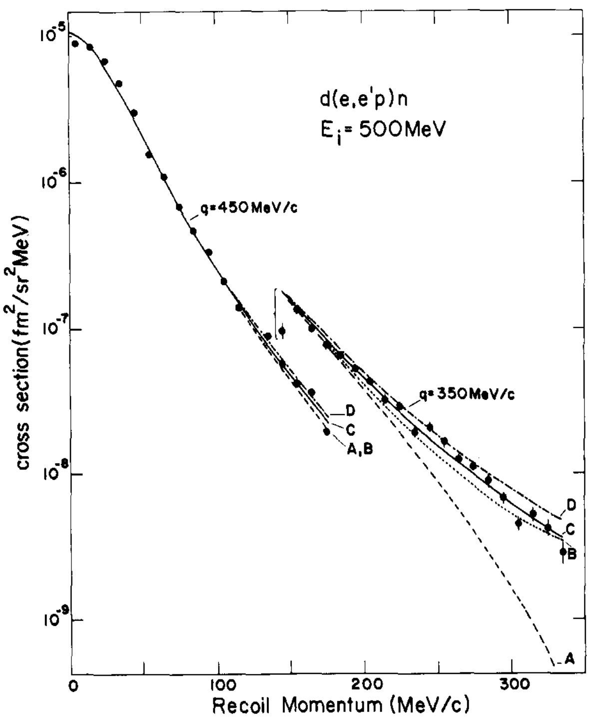

Fig. 2. The d(e, e'p)n cross section as a function of the recoil momentum. The experimental points from ref. [6] are renormalized by a factor 1.69. Curve A gives the result for S-state deuteron, curve C is the result if the deuteron D-state is taken into account (PWIA). The curves B(D) give the result of final state interactions (exchange currents) for the full deuteron wavefunction.

effect of these corrections is small compared with the effect of including the D-state. The data [6] were taken at E_i = 500 MeV and two different q values: q = 450 MeV/c, θ = 59° and q = 350 MeV/c, θ = 44.4°. The direction of $\boldsymbol{q}$ was taken in between $\boldsymbol{k}_i$ and $\boldsymbol{p}_f$. We have renormalized the data by an overall factor of 1.69. This factor represents an estimated 25% effect from radiative corrections, plus an instrumental correction for the target thickness [6]. We find that inclusion of the D-state predicted by the RSC interaction leads to fairly good agreement with the data. We have not made χ^2 fits nor have we considered other values of the normalization factor.

Quasi-free neutron kinematics. We now consider whether it is feasible to get information about the neutron electric form factor G_E^n in a similar experimental setup. The usual approach, quasi-elastic e–d scattering, involves measuring the ratio of ep and en cross sections at the quasi-elastic peak thereby minimizing uncertainties associated with the two-body wavefunction. To our knowledge even in the most recent of these experiments [7] it has not proved possible to do more than set limits on the departure of G_E^n from zero.

However, the coincidence quasi-elastic scattering d(e, e′p)n may prove useful. By detecting the recoiling proton and varying the outgoing electron energy and/or angle one can selectively explore the kinematical region where the cross section is most sensitive to G_E^n. It is necessary to find a compromise between the following constraints: (i) the kinematics should be chosen not too far from quasi-free kinematics to ensure a reasonable cross section, (ii) the proton energy must be large enough for it to escape from the target, and (iii) momentum transfer must not be too large in order to minimize the effects of G_M^n.

As an example we have calculated the cross section at E_i = 500 MeV for fixed p_f (corresponding to E_p = 12 MeV) and fixed t (t = 0.2 (GeV/c)^2). Since p_f is much smaller than n_f the impulse approximation cross sections (solid lines in fig. 3) have been calculated with the neutron current in eq. (2). In the present case in which the knocked out proton is almost at rest, the effect of any reasonable non-vanishing value of G_E^n is likely to be masked by the dominant photon-proton vertex in combination with any process involving momentum transfer to the neutron ‡1.

‡1 We thank A.D. Jackson for bringing this point to our attention.

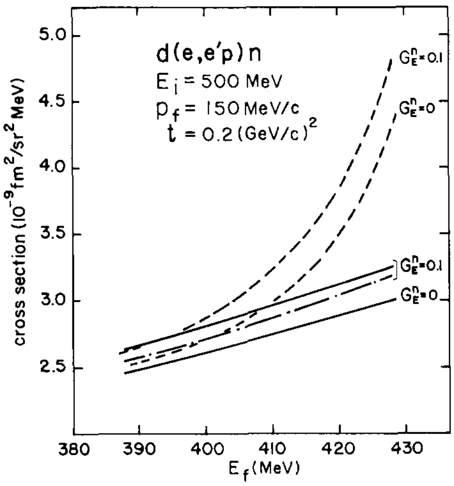

Fig. 3. Calculated d(e, e′p)n cross section at quasi-free neutron kinematics as a function of the final electron energy. The solid lines represent the PWIA result, the broken lines give the result with final state interactions, and the dashed-dotted curve the result including the pair current (no f.s.i.).

Therefore we stress here the corrections from final state interactions and exchange currents; these are shown by the dashed (dashed-dotted) lines in fig. 3. Indeed we note how the exchange current can simulate a non-vanishing G_E^n. This agrees with a similar conclusion of Jackson and Hadjimichael as quoted in ref. [8].

We note that in the present calculation no effect from the isobar current has been taken into account. From the results in refs. [2,9] it may be inferred that for kinematics not too far from the quasi-elastic ridge and low relative n–p energy ($E_{np} \sim 10$ MeV) the contribution of the isobar configuration is small compared to that of the meson exchange current. With increasing energy transfer the effect of the isobar current is expected to become more important; in a more detailed calculation of the present case ($E_{np} \sim 50$ MeV) its effect should be investigated.

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